1-3

VAP - VAPORIZATION

KET - JET ENGINE

FUE - FUEL

PRELIMINARY TESTING OF AN EXPERIMENTAL APPARATUS DESIGNED FOR STUDY OF FUEL SPRAY VAPORIZATION IN JET ENGINE COMBUSTORS

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SUMMARY

The rational design of high output combustors for jet propelled aircraft requires an accurate knowledge of liquid vaporization rates. A possible means of acquiring this knowledge is through the use of an experimental test apparatus which simulates the preignition zone of a combustor. Such an apparatus with the proper instrumentation can provide the experimental data necessary to calculate the heat transfer involved in the vaporization of a fuel spray. It is believed that this heat transfer data in conjunction with a mean drop size for the spray can be correlated with theoretical single droplet calculations[1] to obtain vaporization rates. This project, performed in conjunction with Farnsworth[6] who designed a test apparatus for the study of fuel spray vaporization processes, was concerned with the fabrication and testing of the experimental test apparatus.

Preliminary test runs were made to determine the limitations and capabilities of the test equipment. It was found that the test equipment in its original configuration was severely limited in its ability to provide controlled independent variation of the boundary condition parameters of interest in fuel spray studies. Some redesign and modifications were incorporated into the test equipment, however, budgetary limitations did not permit immediate implementation of all modifications that appeared desirable.

In an effort to show the possibilities of the experimental equipment and to indicate the method of attack proposed, data were obtained for temperature changes due to the vaporization of a fuel spray in air streams of various velocities. These data were

essentially point surveys since control over the boundary parameters, other than air stream velocity, was not possible. Therefore, the effects of velocity changes could not be isolated and studied.

It is believed that the tests performed indicated that the basic test apparatus and the method of attack proposed offer many interesting possibilities in the study of fuel spray vaporization processes. It is recommended that this work be continued. Detailed recommendations for modification of the test equipment and suggestions of how to proceed with the over-all project are included in this paper.

INTRODUCTION

Statement of the Problem

The rational design of high output combustors for jet propelled aircraft requires an accurate knowledge of the phases which a heterogeneous mixture of air and fuel passes between the point of fuel injection and the point where ignition occurs.[1] This ignition delay period can, for purposes of discussion, be divided into physical and chemical components, although no clear-cut division exists in the actual case and the relative magnitudes of the two components is not known. The physical component, i.e., the vaporization component, must inevitably precede the chemical component, at least partially. Obviously, knowledge of the magnitude of and the factors affecting the physical component is of great importance in any study of the ignition delay period and knowledge of the ignition delay period is of prime importance in combustor design.

When a liquid fuel is injected into the preignition zone of a ramjet, turbojet, or an afterburner, the fuel is believed to go through the following stages: The fuel leaves the nozzle orifice as a ligament or sheet. The ligament then quickly breaks up into a large number of various sized droplets. As soon as the droplets are formed there is a tremendous increase in the surface area of the liquid exposed to the air and appreciable heat transfer from the combustion chamber air to the fuel then becomes possible. As the heat transfer takes place, the droplets heat up and start to lose their mass by vaporization and diffusion into the air.

The droplet size and velocity relative to the air both have marked effects on the heat and mass transfer. From the moment of their formation, the droplets are subjected to aerodynamic drag forces which tend to reduce the relative velocity between the droplet and the combustion chamber air stream. After a certain time has elapsed, each individual droplet reaches an equilibrium temperature equal to the wet bulb temperature corresponding to the boundary conditions obtaining for that droplet at the moment and the droplet remains at its wet bulb temperature until it has completely vaporized.

The smaller droplets reduce their relative velocity rapidly and give up their mass and completely vaporize relatively rapidly, so they travel as droplets only a short distance into the combustion chamber. The larger droplets are slower in reaching their equilibrium conditions and in completely vaporizing. In fact, some of the larger droplets are probably not completely vaporized until they move into the actual zone of combustion. A cloud of vapor from the smaller droplets, the vapor being given up by the larger droplets, plus what remains of the larger droplets move down the combustion chamber to some point where a combustible mixture is formed and ignition may be instigated at that point.

Numerous investigators have made detailed studies of various individual problems which are integral parts of the over-all vaporization problem. For example: drop size distribution data,[2,3] vaporization rates and heat transfer coefficients for liquid drops,[4] pressure effects on vaporization rates of droplets in gas streams,[5] and many others.

El-Wakil, Uyehara, and Myers[1] have made a very searching theoretical investigation of the mechanism by which single fuel droplets vaporize in an air stream. It is with their work as background that this project is undertaken.

Method of Attack

It is fully realized that the complexity of the fuel spray vaporization process is such that a purely analytical approach to the problem is not feasible now nor will it likely be so in the near future. However, it is believed that an experimental approach to obtain data which can be used in conjunction with the continuity, energy, and momentum, equations hereafter referred to as the basic fluid flow equations may serve to (1) provide useful information about the effects of various parameters on spray vaporization, (2) provide information in regard to the design of apparatus to experimentally study sprays, (3) indicate the usefulness of the fluid flow equations (with necessary assumptions) as a tool for spray analysis, and (4) provide a means to correlate the experimental spray data with the theoretical single droplet studies to obtain vaporization rates.

It is believed that the experimental measurement of any one or all of the following parameters: static pressure change, static temperature change, and/or velocity change; will serve to give reasonable data for the heat transfer involved in the vaporization process. This heat transfer data then can be used in conjunction with a mean drop size for the spray to obtain mass transfer (vaporization) data by correlation with previous work.[1] Provision for control of the various boundary conditions affecting the fuel spray

vaporization offers the possibility of studying the effects of variation of the boundary conditions on the vaporization process.

Farnsworth[6] designed an experimental apparatus (essentially a small open circuit wind tunnel) with a test section especially fitted out to simulate that portion of a jet engine combustion chamber in which the fuel spray vaporizes. The instrumentation and controls provided were incorporated for the specific purpose of providing a piece of test apparatus to study fuel sprays by the method of attack outlined above.

This project, then, proposed to (1) work with Farnsworth in the fabrication of the test apparatus, (2) test this apparatus to determine its limitations and capabilities as a tool in fuel spray studies, and (3) use a portion of the experimental data obtained during the test runs to check the feasibility of using the fluid flow equations in fuel spray studies. The original, more ambitious, proposals visualized making actual spray vaporization analyses to study the effects of one or more of the boundary conditions. Technical difficulties and time requirements forced abandonment of the latter proposals.

TEST EQUIPMENT

General Description

The design of the experimental apparatus used in this investigation was reported by Farnsworth.[6] The experimental apparatus was built by Farnsworth and this writer in the Mechanical Engineering Laboratories at the University of Minnesota. Although a fairly comprehensive description of the test equipment will be made here, the reader is referred to Farnsworth for a detailed analysis of the design considerations which were incorporated in the wind tunnel.

Figure 1 shows a schematic diagram of the wind tunnel and its air supply system as it was originally designed. It is to be noted that this original design differs from the final design, shown schematically in Figure 2, only in the means of providing the air flow through the tunnel and the necessary piping and valve changes. In the original design the air flow was furnished by the use of a four-cylinder, four-cycle Wright Gypsy aircraft engine, Figures 5 and 6, which had been modified to serve as a two-cycle suction pump. The prime mover for the suction pump was an eight-cylinder Hudson automobile engine. When preliminary tests were started it was discovered that the volumetric efficiency of the suction pump was considerably lower than had been anticipated, in fact, so low that reasonable test section velocities were unobtainable.

The rigid time schedule and the unavailability of a suitable replacement suction pump made it necessary to redesign for a different air supply. A centrifugal compressor having ample capacity for the air flow desired was available and was incorporated into the

wind tunnel system as shown in Figure 2. The compressor and its prime mover, a 165 horsepower Lycoming tank engine, are shown in Figure 7. The Lycoming engine was not equipped with a governor and had to be controlled by a throttle adjustment made at a remote control station shown in Figure 8.

Figures 3 and 4 show the layout of the wind tunnel and its pertinent dimensions.

The air flow path was from the compressor into a large manifold and thence into the wind tunnel intake ducts. A by-pass valve was provided to allow for fine adjustments of air flow since the compressor, driven by an ungovernored engine, was subject to flow fluctuations. The air then passed through an air rotometer and into the outside jacket of the heater section, Figures 10 and 11. Although there is a throttle valve shown in Figure 2, this valve served no useful purpose in the equipment when the air supply was furnished by the compressor.

The heater section has design provision for 12 Chromolax 230 volt, 2450 watt, fin-strip electric heaters. The heater section, with its jackets providing some preheat, should produce air temperatures of approximately 500 F when the test section air velocity is 50 feet per second, according to design calculations.[6] Budgetary limitations precluded the installation of all 12 heaters during the original assembly of the equipment. All experimental data reported in this paper was taken with the preliminary installation of only six heaters.

The air flow then proceeds through the settling chamber, Figure 12, provided with screens to damp large scale turbulence, is accelerated through a nozzle, and flows into the test section.

The test section, shown in Figures 13, 14, and 15, has a square cross-section with inside dimensions of 4 inches by 4 inches and a length of 20 inches. The test section is provided with glass side walls for visual and photographic observation. Static pressure taps are provided along the longitudinal center line of the top wall at one inch intervals for the entire length of the test section. Taps for the insertion of temperature and velocity probes are provided in three planes (1) upstream, approximately in the plane of fuel injection, (2) survey station No. 1, approximately 10 3/4 inches downstream from the point of fuel injection, and (3) survey station No. 2, approximately 18 3/4 inches downstream from the point of fuel injection. The locations of the taps are indicated by the probes and the plugs, used to close unused taps, in Figure 14. At the two survey stations the taps provide for a complete survey of the test section in the vertical direction at three horizontal positions, located one inch from each side wall and at the horizontal center line.

The fuel is injected into the air stream through a Monarch, 5 gallon per hour, 30 degree cone, high-velocity fuel nozzle located on the test section axis at the test section entrance. The fuel system consists of a fuel reservoir, flow meter, pressure gage, control valve, and the necessary piping. Compressed CO_2 provides the pressurization for the fuel system. A one-half inch water pipe supported by guy wires at the settling chamber exit was used

to hold the nozzle in position and serve as a cooling water return jacket for the fuel cooling water. The fuel and the cooling water are carried to the area of the fuel nozzle by one-fourth inch and three thirty-seconds inch copper tubing, respectively, which are located inside the one-half inch water pipe and indicated in Figure 17.

The fuel-vapor air mixture, after leaving the test section, proceeds through a diffuser into a surge tank, Figure 16, equipped with safety blow-out valves to relieve the pressure in case of accidental ignition or explosion. From the surge tank the fuel-vapor air mixture was ducted into a large manifold and exhausted to the atmosphere.

Instrumentation

Air flow was measured by the air rotometer or calculated by the use of the velocity, temperature, and pressure measurements. Air stream temperature was measured by a shielded thermocouple located at the entrance of the test section. A mercury manometer, center left of instrument panel, Figure 19, connected to a static pressure tap located approximately at the test section entrance, was used to establish the gauge static pressure reference level. As is indicated in Figure 22, this reference pressure is connected to the reservoir of the alcohol manometer bank, right side of instrument panel, so that the readings of the alcohol manometers indicated differential pressure readings in the cases of the static pressure readings and indicated the dynamic pressure readings for the velocity probes. The two outside alcohol manometers were connected to the two velocity probes. All other alcohol manometers were connected to the static pressure taps along the test section top wall. An

inclined manometer, upper left of instrument panel, was provided to obtain more accurate readings of static pressure differences between the plane of fuel injection and the survey stations, No. 1 and No. 2. Two total head probes were provided for the measurement of velocity at the test section entrance and at the two survey stations.

Two iron-constantan thermocouple probes with special baffles, designed to deflect liquid droplets away from the thermocouple sensing element, were provided to survey the fuel-vapor air mixture at the two downstream survey stations. Figures 20 and 21 show the general details of the thermocouple probe construction. Since only two thermocouple probes were available, it was necessary to shift the probes to obtain the typical survey patterns as shown in Figure 23. Probe positions are designated by column for horizontal position and by row for vertical position. Further discussion of these probes is offered in the Results and Discussion, since it is believed that they have considerable bearing on the experimental data obtained.

Fuel flow was measured by a fuel rotometer, upper left edge of instrument panel, and the fuel pressure was measured by the fuel pressure gauge. A globe valve located at the exit of the fuel rotometer provided a means of controlling the rate of fuel flow. Fuel temperature was measured by a thermocouple element embedded in the base of the fuel nozzle filter chamber.

All thermocouples were wired to a thermocouple switchboard. A direct reading Leeds and Northrup potentiometer unit was provided so that any desired temperature could be read directly in degrees Fahrenheit by throwing the proper switch on the thermocouple switchboard.

EXPERIMENTAL PROCEDURE

The experimental apparatus as originally conceived and designed offers a tremendous field of possibilities for investigations of fuel spray vaporization processes. The over-all fuel spray vaporization studies may include investigation of the effects of variation of test section entrance temperature, velocity, and static pressure; fuel-air ratio; fuel pressure and temperature; fuels; and possibly several others. The testing program that will be necessary to complete these over-all fuel spray vaporization studies which can be accommodated by the basic experimental apparatus will probably involve several thousand man-hours of work and will be a matter of two or three years in being completed and is far beyond the scope of this project. This project proposed to assist Farnsworth in the fabrication of the experimental apparatus, test the equipment, and then proceed as far as time requirements would allow into the actual fuel spray vaporization studies. Since several hundred man-hours were spent in the fabrication of the equipment, it was realized that the scope of this investigation could proceed little further than testing the equipment.

A series of preliminary test runs were made to check the design calculations[6] and determine the operating limits of the experimental apparatus. Farnsworth[6] made velocity surveys at the two survey stations and reported satisfactory velocity profiles with no large scale turbulence or cross flow. Since the primary objective of this investigation was to test the equipment for vaporization studies, all test runs had to be made in operating limits that would insure sufficient vaporization to produce measurable effects on the

test section air stream. These effects were to be measured as static pressure, static temperature, and velocity changes of the test section air stream.

The preliminary test runs indicated that the equipment as originally built imposed serious limitations on the operating conditions that could be used. These limitations were (1) the velocities attainable with the suction pump configuration were unacceptably low, (2) the air temperatures, that could be obtained with the preliminary installation of only one-half of the heaters, were marginal and almost unacceptably low, and (3) the combination of low velocity and low temperature resulted in little actual vaporization and introduced severe thermocouple wetting problems, particularly at survey station No. 1.

Redesign of the air supply system was undertaken and the problem of too low velocities was eliminated. Concurrent with the air supply redesign, thermocouple probe No. 1 was modified by removing the second baffle and moving the thermocouple element to a point well inside the leading cone baffle. Thermocouple probe No. 2 remained as was and had its thermocouple well back in the probe inside the third baffle, Figure 21. The air supply redesign imposed limitations and caused other difficulties. No satisfactory means of independent control of static pressure and velocity were incorporated in the redesign due to budgetary and time schedule requirements. Therefore, the possibility of study of the effects of static pressure on vaporization was eliminated from this project, since velocity changes always caused static pressure changes.

The redesigned air supply which worked at positive gauge pressures provided a sizeable increase in the air stream density. This density increase in conjunction with the higher velocities, which were necessary to obtain appreciable vaporization, caused a large increase in the mass flow of the air. Since the fuel system had been designed with capacity to give typical fuel-air ratios at the lower mass flow rates of the air, it was found that the fuel-air ratios which could be obtained with maximum fuel flow, and the increased air flow were quite low. Fuel leakage around the exit of the thermocouple leads from the fuel nozzle filter chamber necessitated the use of fuel pressures of 70 psig or less. Several attempts to stop this leakage were made but no satisfactory results were obtained. Consequently, the fuel system had to be operated at pressures of 70 psig or less. The possibility of isolating and studying the effects of typical fuel-air ratios on vaporization was largely eliminated.

By far the most severe operating limitation occurring was the limitation imposed by the attainable air stream temperature. Since the driving force in the vaporization and diffusion process is the vapor pressure of the liquid fuel and since the vapor pressure is an exponential function of the temperature, low temperatures give rise to very small amounts of vaporization. To measure the effects of the vaporization on the test section air stream, it was necessary to obtain the maximum vaporization possible; therefore, it was necessary to use the maximum temperature attainable at all times. To further complicate the temperature problem, the variation of the air stream velocity naturally affected the temperature obtainable since the air stream passed over the heaters at different velocities.

Since the preliminary test runs indicated severe limitations on the operating conditions attainable and pointed out the difficulties of independent control of the variables so that their effects might be isolated and studied, the original test program had to be quite limited in scope. However, it is believed that the preliminary test runs served a very useful purpose. The information and experience gained in these runs dictated the procedure to be used for the testing program for this project and served as a basis for most of the recommendations, offered later, for design refinements of the test equipment.

The test program consisted of a series of runs at four different velocities (101, 122, 155, and 179 feet per second), since velocity appeared to be the variable most subject to reasonable controlled variation. The odd numbers used for velocities were due to the fact that predetermined dynamic pressure heads, which were used in the actual runs to set the velocity, were based on estimated temperatures. The precalculated dynamic heads were for velocities of 100, 125, 150, and 175 feet per second. It should be noted that these runs were of little or no value in studying velocity effects on vaporization since the other variables such as test section entrance static pressure, static temperature, and fuel-air ratio were not under control.

Each run, which is defined as the taking of a complete set of data at a particular velocity, consisted of two parts. First a complete temperature survey at each of the two downstream survey stations with a survey pattern as indicated in Figure 23 was made with no fuel being injected into the test section. This part of

the run provided a means of obtaining a temperature profile of the dry air stream which could be used for calibration purposes. Then the survey was repeated with fuel injection. The fuel used for these runs was benzol. During the second part of the run, attempts to measure static pressure and velocity changes were made, but with no success. As indicated by Sample Calculation No. 1 of Appendix B, these variations were very small and were largely masked by fluctuations of the flow caused by compressor RPM fluctuations.

The actual mechanics of conducting each run were duplicated as nearly as possible for each run to minimize possible errors. The engine and compressor were started and the wind tunnel heaters turned on. Approximately one to one and one-half hours of operation of the equipment with low air velocities was needed to heat up the mass of steel in the wind tunnel and let the temperatures stabilize. Approximately 10 to 15 minutes before a run was started, the compressor was brought up to sufficient RPM and the by-pass valve adjusted to set the dynamic pressure to a precalculated value to give the desired test section velocity. The dynamic pressure reading was checked every few seconds and the by-pass valve adjusted to maintain the desired velocity as nearly constant as possible.

As soon as the test section entrance air temperature became restabilized, it was possible to start the run. One operator set the thermocouple probes by steps to each of the positions shown in Figure 23, and maintained the adjustment of the by-pass valve to maintain constant velocity. A second operator read and recorded the temperature data for the entrance air and the two survey stations.

The second operator also controlled the fuel flow and recorded fuel flow, fuel temperature, and fuel pressure readings. Each run, therefore, consisted of 104 survey temperature readings, 104 readings of entrance air temperature, and the accessory fuel data. Each thermocouple probe was used to take readings in each position of each survey station for each run. It was believed that this was necessary to provide a possible cross-check on the experimental data or to indicate any differences in the behavior of the thermocouple probes.

RESULTS AND DISCUSSION

This investigation was designed to test the experimental apparatus designed by Farnsworth[6] and to obtain what experimental data that time limitations would allow. The results of the preliminary testing of the equipment have been discussed in the Experimental Procedure section of this paper, since a history of the results of the preliminary tests dictated the experimental procedure that was followed.

The experimental data that were obtained are shown in Tables I and II. These data were reduced by the method explained in Appendix A. In the process of reducing the data, it was noted that the dry survey data were practically constant for each individual probe position at a particular survey station regardless of velocity or of the probe used. It was decided that a single calibration correction sheet for each survey station would be used in the processing of the data. These two calibration sheets, Figure 24, also present a picture of the temperature profiles at the two survey stations. It must be remembered, when using the calibration figures to visualize a temperature profile, that plus corrections indicate temperatures colder than the reference level and minus corrections indicate temperatures warmer than the reference level.

The temperature profiles which were obtained are not satisfactory but time schedule requirements did not permit time for corrective measures. It is believed that the installation of the remaining six heaters will correct this problem; however, if it does not, then guide vanes to redistribute the flow over the heaters will probably have to be incorporated into the wind tunnel.

As was previously mentioned, the experimental data obtained is of little value in showing the effects of varying velocity on the vaporization process. This, of course, was due to the fact that the other variables were not under control and the effect of velocity variation could not be isolated and studied. This experimental data then is essentially a point survey of several individual points and serves primarily as a test of the equipment and instrumentation.

The experimental data of Tables I and II are plotted in Figures 25 through 32. The plots show general trends that were to be expected. The temperature drops were the greatest near the longitudinal axis of the test section. This effect is due primarily to the fact that the local fuel-air ratios are considerably higher in this portion of the air stream. More vaporization takes place in this area of high fuel-air ratios and more heat is extracted from the air stream, thus the higher temperature drops. Another consideration to keep in mind is the fact that the vapor formed in the outer portions of the air stream becomes a part of a lean mixture. The preponderance of hot air in the outer portions of the stream tends to superheat the mixture. This latter effect tends to give small temperature drops in the outer portions of the test section.

The experimental data provides some very interesting information regarding thermocouple probe design for measurements of temperature in wet mixtures of fuel-vapor and air. Both thermocouple probes were used to measure temperature at each position in all test runs. It was noted that the No. 1 probe always gave lower readings than the No. 2 probe when reading the wet mixture air stream temperature. This indicated that the probes reacted differently when exposed to

the wet mixture air stream, although no such differing reaction had been noted in the dry survey data.

A thermocouple element reports the temperature which the thermocouple itself attains. In nonflow problems the thermocouple essentially reaches the temperature of its surroundings and therefore can be used to report the temperature of the surrounding medium. Such is not the case when the medium moves past the thermocouple. The thermocouple still reports the temperature that it attains, but this temperature depends on the balance of heat transfer to and from the thermocouple itself. In the thermocouples under discussion, it is believed that the heat flow to the thermocouple comes primarily by convection from the air flow over the thermocouple. The heat flow out is believed to be the result of radiation of the thermocouple to the baffle surrounding it.

With these considerations in mind the following possible explanation for the thermocouple reaction is offered. The air or vapor-air mixture flow over both thermocouples was essentially the same, although the baffles on the probes differ slightly. The baffles protected the thermocouples from the liquid droplets so no wetting of the thermocouple element itself was normally present. Therefore, the heat flow to either thermocouple was essentially equal. During dry runs all the baffles on both probes reached approximately equal temperatures. Since the heat flow from the thermocouple depended on the temperature of the body to which heat was being radiated, thus the heat flow from each thermocouple was essentially equal. The heat flow then balances at the same point

and the thermocouples should reach and report the same temperature, as was the case in the experimental dry survey runs. During the wet runs it is believed that the forward baffle of a probe is partially wetted by fuel droplets and assumes a considerably lower temperature than the back baffles. Therefore, the thermocouple of probe No. 1 which is located within and is radiating essentially to the forward cone baffle would attain and report a lower temperature than the thermocouple of probe No. 2 which is located in and is essentially radiating to the third baffle on its probe.

It is believed that the readings obtained with thermocouple No. 2 represent the most accurate data. It is fully realized, however, that this data may contain considerable error, since the problem of measuring the temperature of a moving wet mixture is far from solved.[7] The design and development of a reliable thermocouple probe for temperature measurements in a moving wet mixture would be an accomplishment of considerable stature and would be an invaluable aid in the study of fuel sprays.

Sample calculations are presented in Appendix B to indicate the method of using the experimental data in conjunction with the equations of continuity, energy, and momentum. These equations reduce to the case of three equations and four unknowns. If one unknown can be experimentally determined, then it is possible to solve for the other unknowns. This was the case of the work done in Sample Calculation No. 1 of Appendix B. In case two or more of the unknowns can be determined experimentally, then the equations provide a means of cross-checking the experimental data as well as a means of solving for the other unknowns.

Sample Calculation No. 2 of Appendix B was made to indicate the possibility of obtaining more realistic experimental data with the basic test apparatus slightly modified. It is to be noted that the use of a higher entrance air temperature, a higher fuel-air ratio, and a fuel with slightly higher latent heat of vaporization would provide significant changes in static pressure and velocity.

Although the equations provide a complete solution with the experimental measurement of any one parameter, it is believed that a much better experimental analysis of fuel spray vaporization processes can be made if all three experimental measurements can be obtained and cross-checked against each other. It is believed that the experimental measurement of static pressure changes offers the best possibility of obtaining accurate data if the equipment is operated within limits to provide measurable changes in this parameter. It was the original intent of this investigation to depend primarily on experimental data for static pressure changes as a means for solving the fluid flow equations; however, the operating limitations imposed by the present test equipment configuration forced the dependence on the temperature data.

The results of this investigation have shown the operating limits of the test equipment in its present configuration. The experimental data that were obtained showed the possibility of measuring some of the parameters that are of importance in the study of fuel spray vaporization processes. Sample calculations verified the need for modification of the test equipment so that more realistic experimental data might be obtained. Further modification of the

basic test apparatus to provide for independent control over various parameters, i.e., entrance static pressure, temperature, fuel-air ratio, etc., so that they may be isolated and their effects studied, will provide future investigators with a very useful tool to study fuel sprays. The addition of photographic equipment capable of determining drop size distribution will open up the possibility of correlation of experimental spray data with El-Wakil's[1] theoretical single droplet analysis so that actual rates of vaporization may be determined.

CONCLUSIONS AND RECOMMENDATIONS

From the preliminary tests and the foregoing discussion it is concluded that:

1. The test apparatus in its present configuration is not a satisfactory tool for the study of fuel spray vaporization processes.
2. The test apparatus in its present configuration gives sufficient indication of its future possibilities to warrant the expenditure of time and money for design modifications and refinements.
3. Completion of the heater installation and modification to provide for independent control of static pressure, temperature, velocity, and fuel-air ratio over wide operating ranges will provide a highly satisfactory experimental tool for fuel spray studies.
4. The use of the fluid flow equations as a tool in analysis of experimental data appears reasonable, although insufficient experimental data were obtained to provide conclusive results.

Suggestions for future investigators using this basic test apparatus are submitted as follows:

1. A more stable air supply should be obtained. Operation of the system under partial vacuum is already provided for in the wind tunnel construction and would appear to best simulate the conditions of most interest in combustion chamber design.

2. The remaining six heaters should be installed and the wind tunnel should be insulated from the heater section to the test section to provide sufficiently high air temperature to insure appreciable vaporization. A variac should be installed in one of the heater circuits to provide temperature control.
3. A system to provide for independent control of test section static pressure and velocity should be incorporated.
4. A design study of the thermocouple probes should be made to provide a basis for reasonable engineering estimates of the errors involved in these measurements.
5. The operating limits of the fuel system should be broadened by the installation of a larger capacity fuel rotometer and a larger nozzle. Effective sealing around the exit of the thermocouple leads from the fuel nozzle holder should be incorporated to allow higher fuel pressures.
6. Provision for photographic equipment capable of recording drop sizes should be considered.

APPENDIX A

TEMPERATURE DATA REDUCTION PROCEDURE

The temperature measurements at each position of each survey pattern consisted of an air steam temperature measurement without fuel injection and a measurement of fuel-vapor air mixture with fuel injection. Since the investigation desired to measure the temperature change due to vaporization, a procedure of data reduction was set up to isolate these changes.

The procedure followed was:

1. The shielded thermocouple located in the test section entrance was used to survey the test section entrance temperature profile.
2. This thermocouple was then placed at a position where it read the mean value of the entrance air temperature. This probe remained fixed in this position throughout all test runs. This thermocouple reading then became the reference temperature reading for the whole test section.
3. The survey probe readings without fuel injection were then taken and two calibration charts, Figure 24, were made. The calibration chart worked in the following manner: The entrance air temperature reads 202 F and the survey probe reads 192 F. A correction factor of plus 10 degrees is then necessary and appears on the calibration chart for this particular position on the survey pattern at the particular survey station. Essentially,

then, the calibration chart makes corrections that indicate a fictitious isothermal profile at each of the two survey stations.

4. The survey probe readings were then taken with fuel injection and the proper calibration corrections applied. These corrected readings were then subtracted from the entrance air reference temperature and the temperature changes due to vaporization were obtained.

A sample calculation for probe No. 2, station No. 2, positioned on the test section axis follows:

Calibration data	-	$T_a = 202$ F	$T_{a2} = 192$ F
Correction	-	$202 - 192 = +10$	
Survey data	-	$T_a = 211$ F	$T_{m2} = 181$ F
		T_{m2} + correction = 191 F	
		$\Delta T = 211\text{ F} - 191\text{ F} = 20\text{ F}.$	

It is to be noted that the entrance air temperature reference level varied by several degrees during the runs. Since no control of the temperature reference level was available, these variations had to be accepted. However, it is believed that no appreciable error was thus introduced because temperatures were corrected to the reference existing at the time that the various readings were made.

APPENDIX B

USE OF EXPERIMENTAL DATA WITH THE FLUID FLOW EQUATIONS

In order to use the experimental data with the continuity, energy, and momentum equations certain assumptions were necessary. The assumptions made were:

1. Mean values of temperature, static pressure, and velocity may be obtained to represent the cross-sectional profile of the flow at any station. This reduces the problem to a one dimensional analysis.
2. The kinetic energy terms of the energy equation are negligibly small.
3. The specific heat of the fuel-vapor air mixture is a constant and equal to the specific heat of the air at the temperature of the entrance air.

The following sample calculation indicates the procedure followed and uses the data from the experimental test run at a velocity of 101 feet per second, survey station No. 2, thermocouple probe No. 2. The temperature differences from Figure 26 were used to obtain a mean temperature drop. The mean temperature drop was obtained by:

$$\Delta T = \frac{\Sigma \Delta T_i \ A_i}{A} = 9.52 \text{ F},$$

where T_i represents any temperature drop on a typical survey pattern and A_i is an area over which the ΔT_i is considered to be effective.

Sample Calculation No. 1

1. Continuity equation,

$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2 \qquad A_1 = A_2$$

$P_{T_1} = 15.67$ psia $\qquad T_a = 670°R \qquad V_1 = 101.8$ fps

$$\rho = p/RT$$

$$\frac{15.67 \times 144}{670 \times 53.3} \times 101.8 = \frac{P_{T2} \times 144}{T_{M2} \times 53.3} \times V_2$$

$$\frac{P_{T2}\, V_2}{T_{M2}} = 2.382$$

$$T_a - \Delta T = T_{M2} \qquad \Delta T = 9.52$$

$$T_{M_2} = 670 - 9.52 = 660.48°R$$

$$P_{T_2}\, V_2 = 2.382 \times 660.48 = 1573.3$$

2. Energy equation,

$$C_p\, T_a + Q = C_p\, T_{M2}$$

$$.241(T_a - T_{M2}) = -Q$$

$$.241(9.52) = 2.29 \text{ Btu/lb air}$$

$$\frac{2.29}{F/A} = 225.5 \text{ Btu/lb fuel}$$

where

$F/A = 0.01014$ is measured experimentally.

3. Momentum equation,

$$(P_{T2} - P_{T1})A = \frac{M_a V_1}{g} - \frac{M_a + M_f}{g} V_2$$

$$(P_{T_2} - 15.67) \times 144 \cancel{g} = \frac{\rho V_1 \cancel{g} V_1}{g} - \frac{1.01014 \ \rho_1 V_1 \cancel{g} V_2}{g}$$

$$P_{T_2} - 15.67 = .1415 - 0.00139 \ V_2$$

from (1) substitute $V_2 = \dfrac{1573.3}{P_{T_2}}$

$$P_{T_2}^{\ 2} - 15.8115 \ P_{T_2} + 2.185 = 0$$

Using the quadratic formula,

$$P_{T_2} = 15.6720 \text{ psia}$$

$$\Delta p = .002 \text{ psi}$$

$$= .0687 \text{ inches alcohol}$$

Using (1) $V_2 = \dfrac{1573.3}{15.672} = 100.4$ fps

$$\Delta V = 101.8 - 100.4 = 1.4 \text{ fps.}$$

The following sample calculation follows the above procedure and uses what are considered to be more reasonable values for entrance air temperature and fuel air ratio. This calculation is presented in an effort to show that higher air temperature and a larger fuel air ratio will cause changes in static pressure and velocity that are readily measurable.

Sample Calculation No. 2

1. Continuity equation,

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2 \qquad\qquad A_1 = A_2$$

$P_{T_1} = 15.67$ psia $\qquad T_a = 960^{\circ}R \qquad V_1 = 100$ fps

$$\frac{15.67 \times 144}{960 \times 53.3} \times 100 = \frac{P_{T_2} \times 144}{T_{M_2} \times 53.3} \times V_2$$

$$\frac{P_{T_2} V_2}{T_{M_2}} = 1.632.$$

2. Energy equation,

$$C_p T_a + Q = C_p T_{M_2}$$ Assume $Q = 550$ Btu/lb fuel

$$.246(T_a - T_{M_2}) = -Q$$ Assume $F/A = .0667$

$$.246(960 - T_{M_2}) = +36.7$$

$$T_{M_2} = 960 - 149.4 = 810.6$$

$$\Delta T = 149.4$$

Using (1) and (2),

$$P_{T_2} V_2 = 1.632 \times 810.6 = 1325.$$

3. $$(P_{T_2} - P_{T_1})A = \frac{M_a V_1}{g} - \frac{(M_a + M_f)}{g} V_2$$

$$(P_{T_2} - 15.67)144 \cancel{A} = \frac{\rho_1 V_1 \cancel{A} V_1}{g} - \frac{1.0667 \rho_1 V_1 \cancel{A} V_2}{g}$$

$$P_{T_2} - 15.67 = 0.0953 - .00099 V_2$$

Using (1) and (2),

$$V_2 = \frac{1325}{P_{T_2}}$$

$$P_{T_2}^2 - 15.7652 P_{T_2} + 1.31 = 0$$

Using the quadratic formula,

$$P_{T_2} = 15.6817$$

$$\Delta P = .0117 \text{ psi}$$

$$= .402 \text{ inches alcohol}$$

Using (1) and (2),

$$P_{T_2} V_2 = 1325$$

$$V_2 = \frac{1325}{15.6817} = 84.5 \text{ fps}$$

$$\Delta V = 15.5 \text{ fps.}$$

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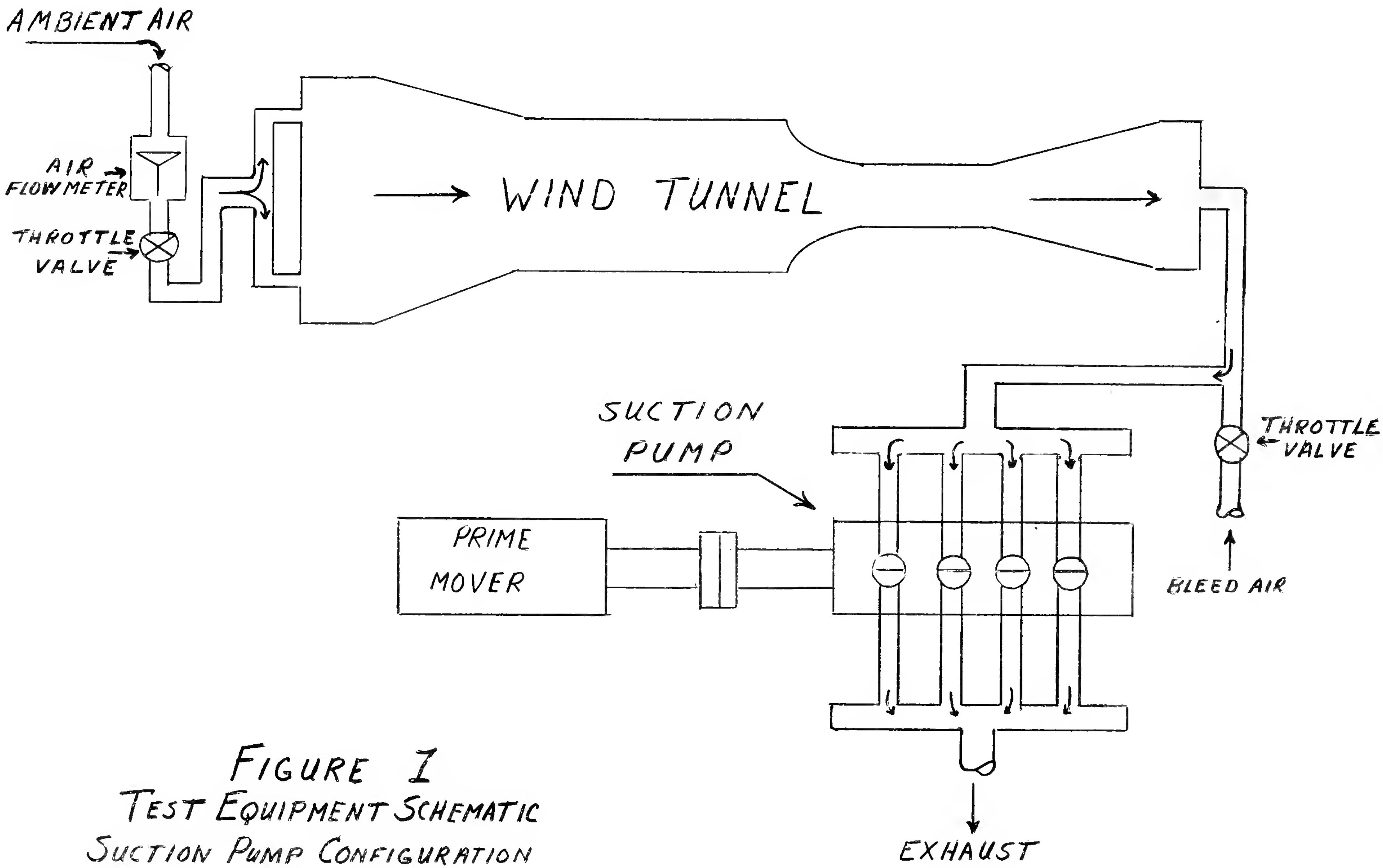


FIGURE I
TEST EQUIPMENT SCHEMATIC
SUCTION PUMP CONFIGURATION

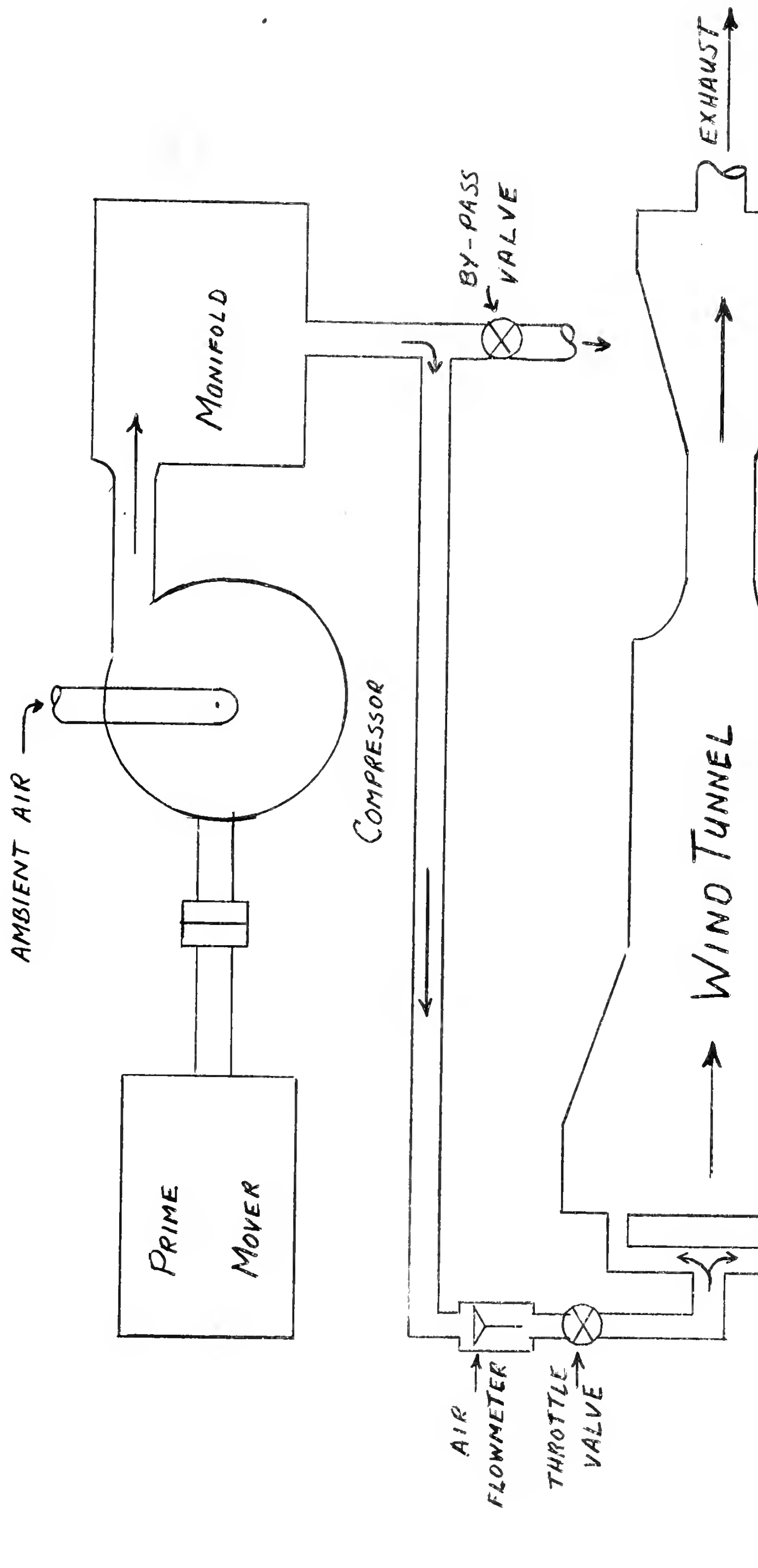


FIGURE 2
TEST EQUIPMENT SCHEMATIC
COMPRESSOR CONFIGURATION

WIND TUNNEL SKETCH
SIDE VIEW

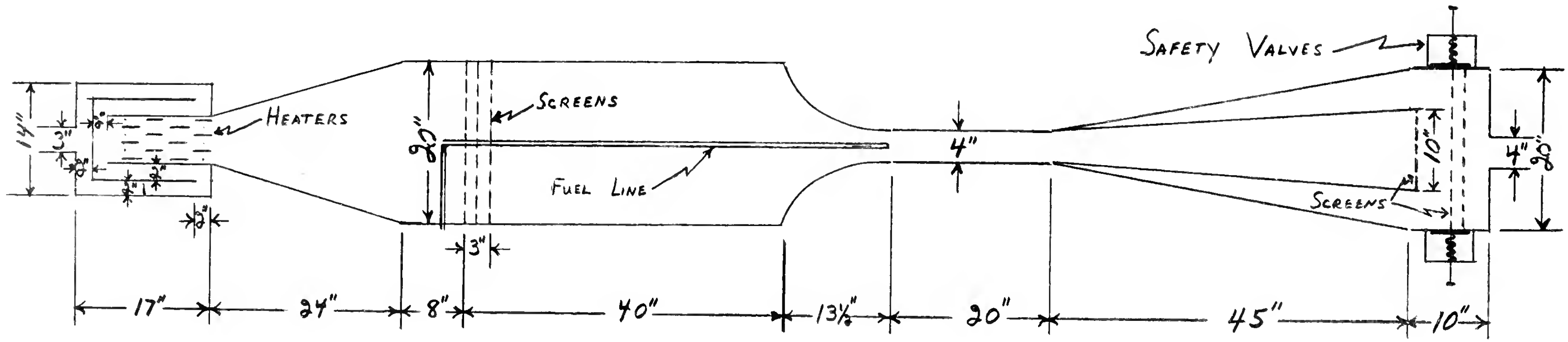


FIG. 3

SCALE 1:20

WIND TUNNEL SKETCH
TOP VIEW

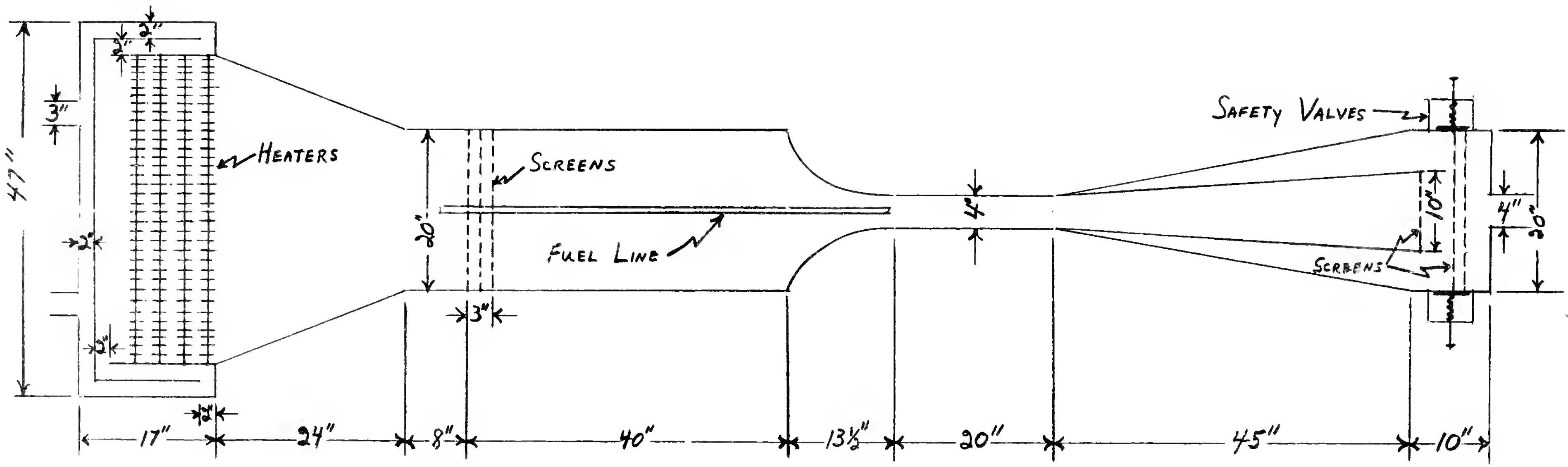


FIG. 4

SCALE 1:20

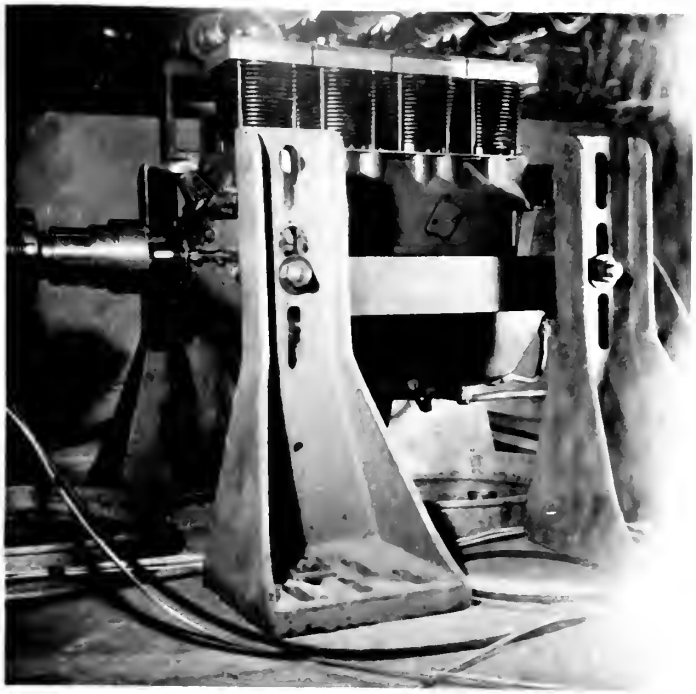
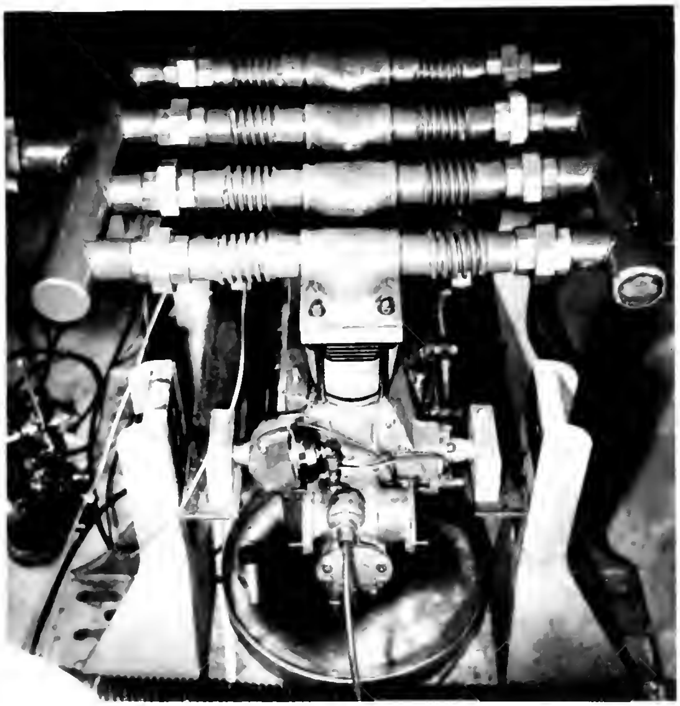


Fig. 5 Suction Pump Side View



Fi . 6 Suction Pump Top View

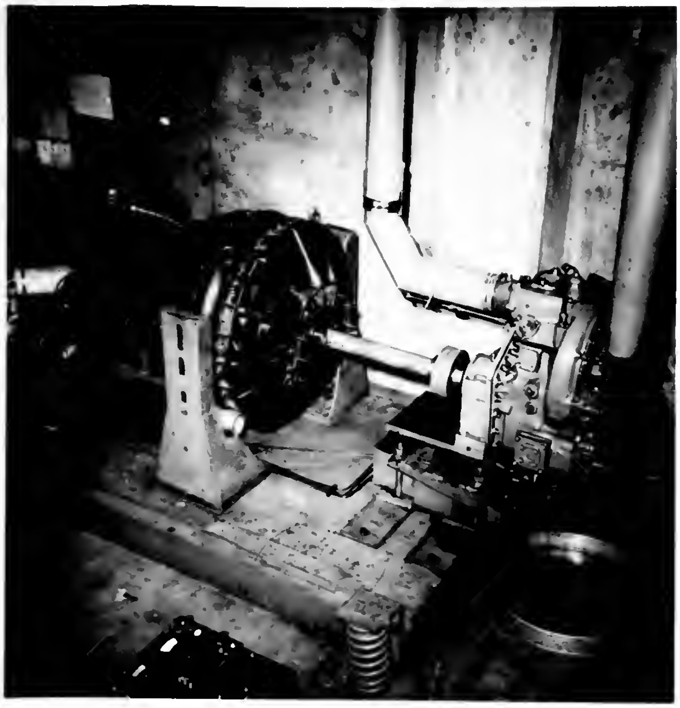


Fig. 7 Engine and Compressor

Fig. 8 Control Panel for Engine Operation

Fig.9 Wind Tunnel and Accessories

Fig. 10 Heater Section Assembled

Fig. 11 Heater Installation

Fig. 12 Settling Chamber and Contraction Nozzle

Fig. 13 Test Section

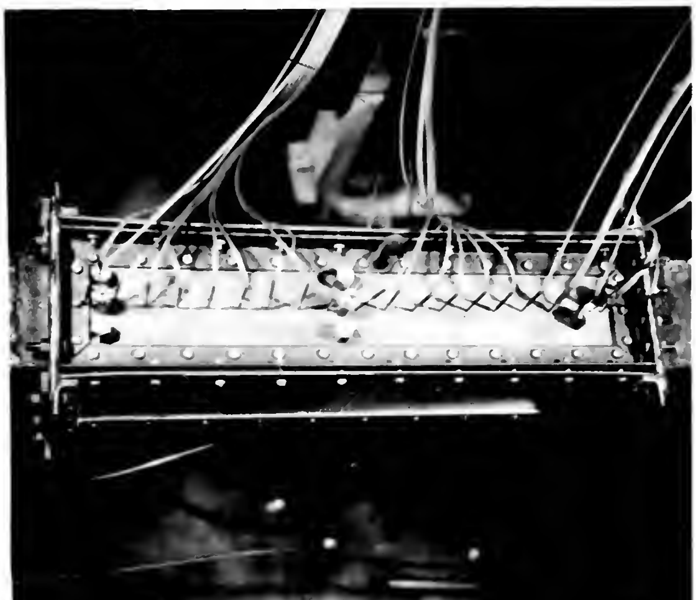


Fig.14 Test Section Top View

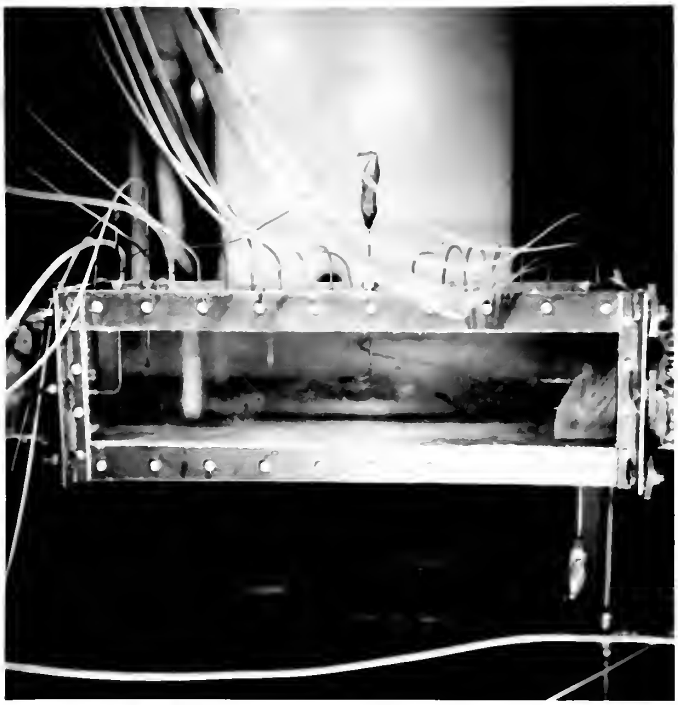


Fig. 15 Test Section Side View

Fig. 16 Diffuser [illegible]

Fuel System

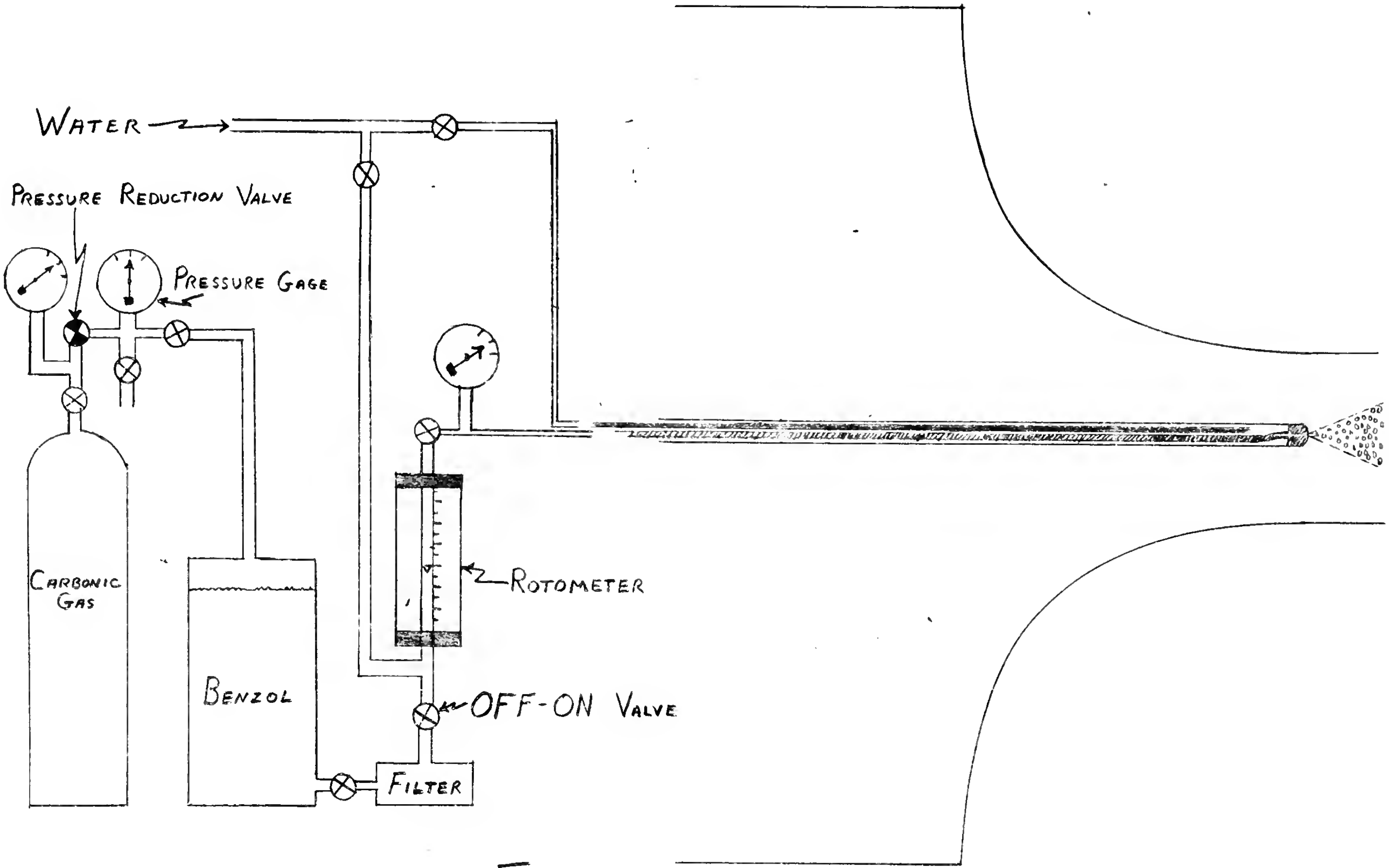


Fig. 17

Heater Electrical Circuit

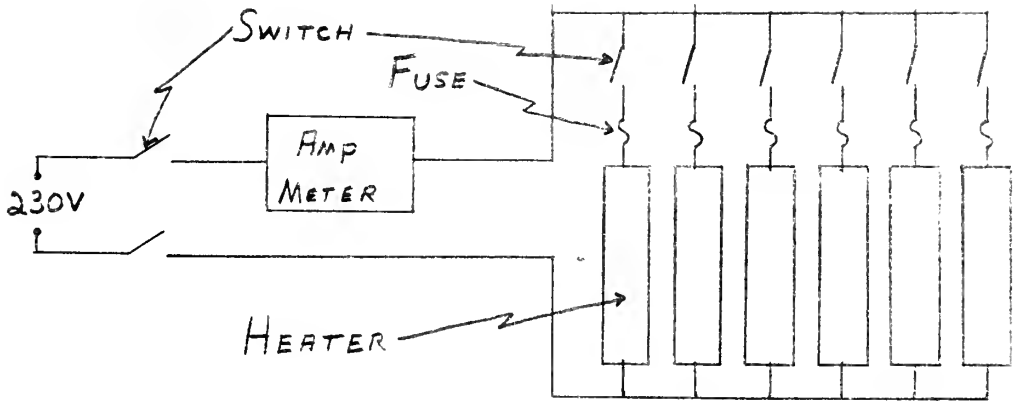


Fig. 18a

Thermocouple Circuit

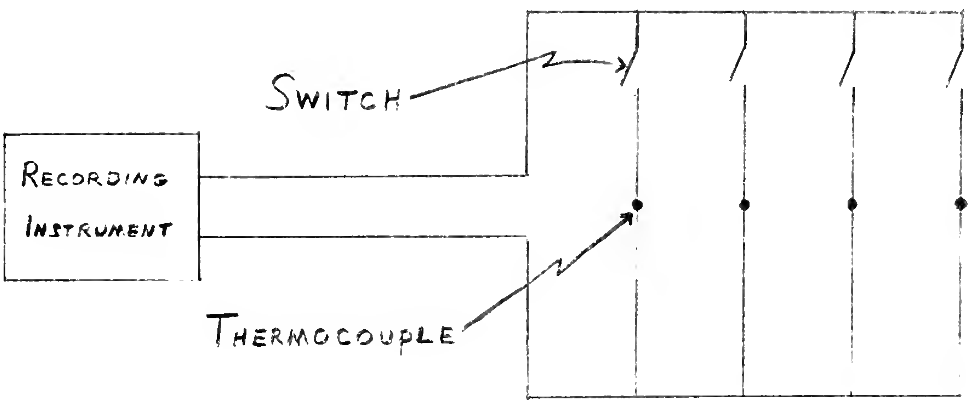
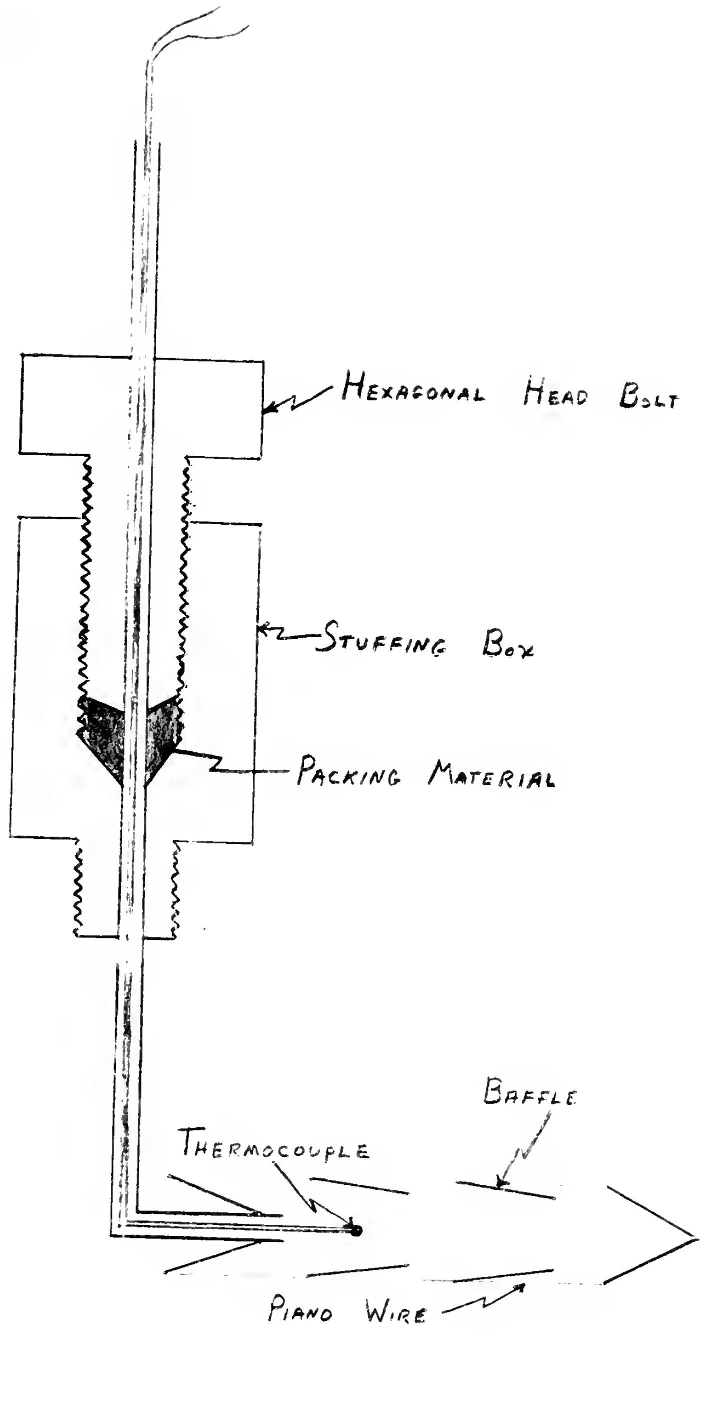


Fig. 18b

Fig. 19 Instrument Panel

Fig. 20 Thermocouple Probe



WET-MIXTURE THERMOCOUPLE AND STUFFING BOX

FIG. 21

PRESSURE MEARURING SYSTEM

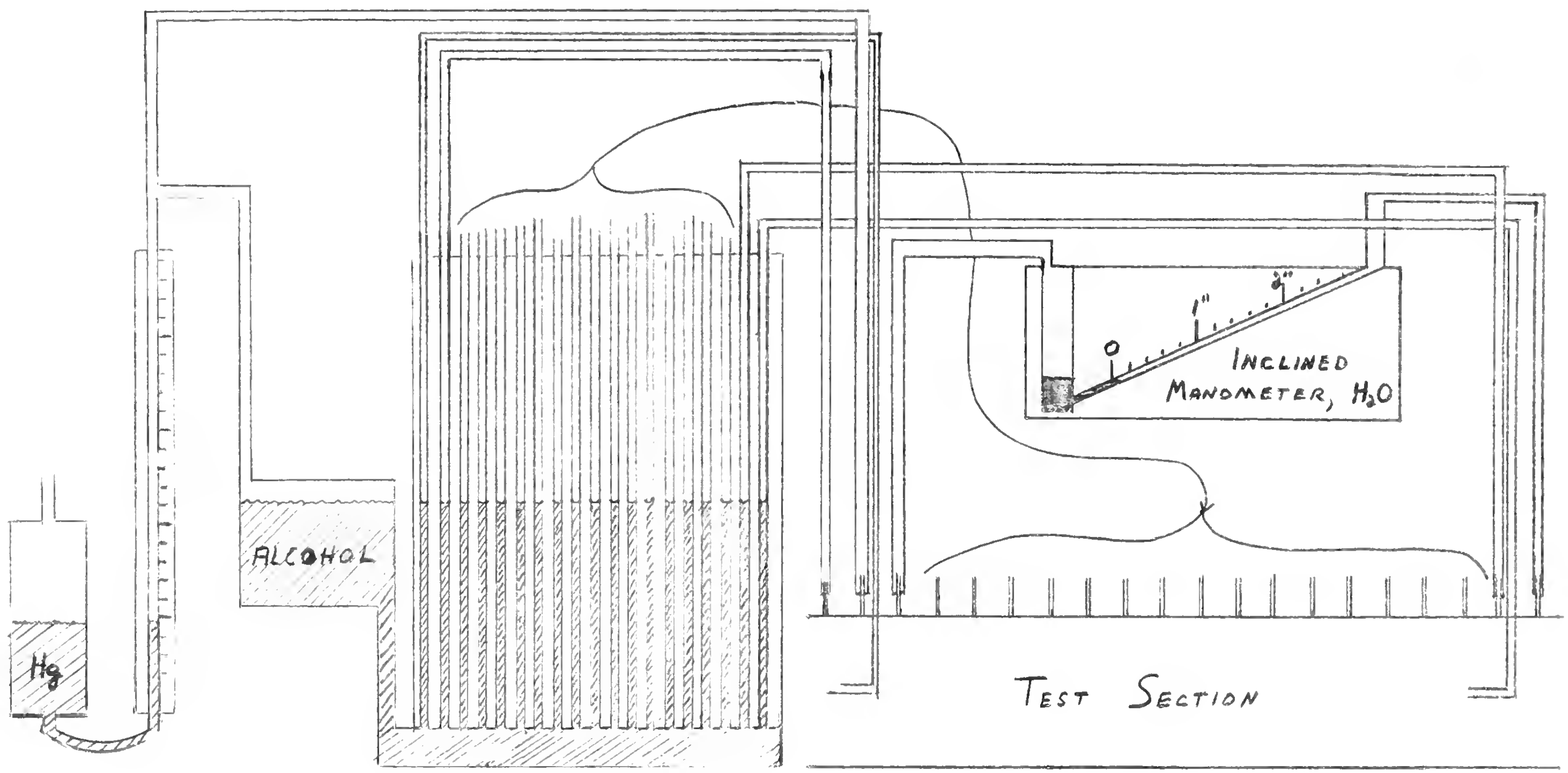


FIG. 22

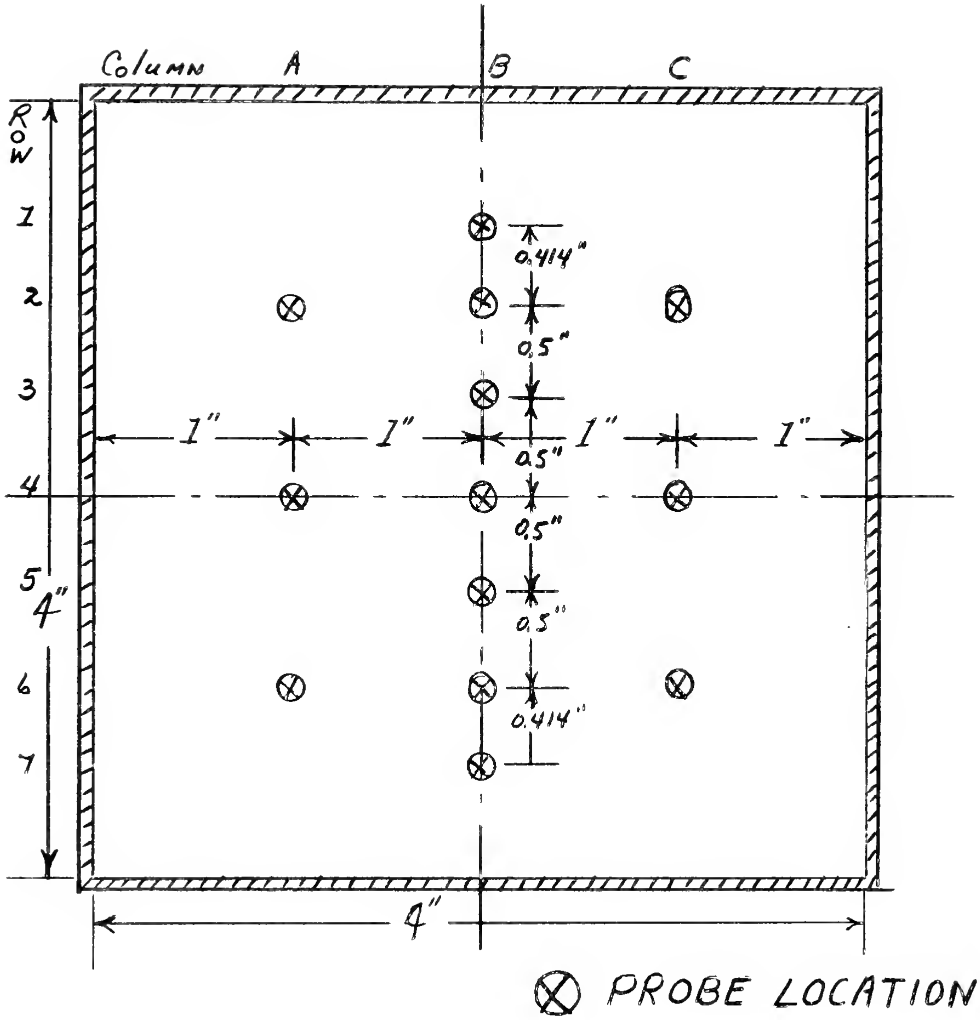


FIGURE 23

SURVEY PATTERN
Looking Downstream

Station No. 1

	A	B	C
1		- 5	
2	+10	- 4	- 2
3		+ 1	
4	- 2	+ 9	0
5		+11	
6	+ 8	+27	+10
7		+30	

Station No. 2

	A	B	C
1		- 4	
2	+ 9	0	0
3		+ 2	
4	+ 1	+ 8	0
5		+16	
6	+10	+28	+18
7		+30	

Figure 24. Calibration Corrections Viewed Downstream

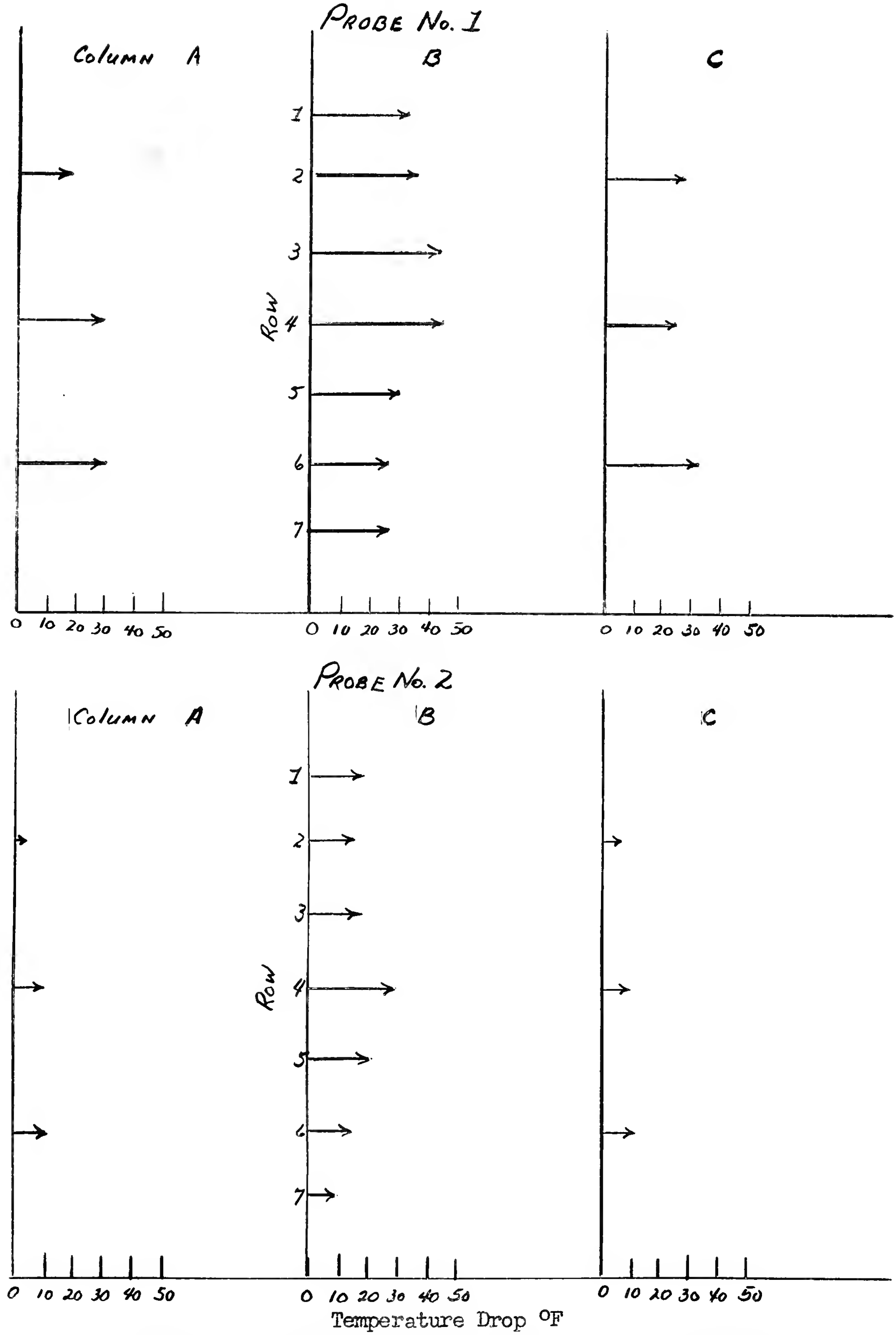


Figure 25. Temperature Drop Due to Fuel Vaporization
Station No. 1, Velocity 101 fps, F/A 0.01014

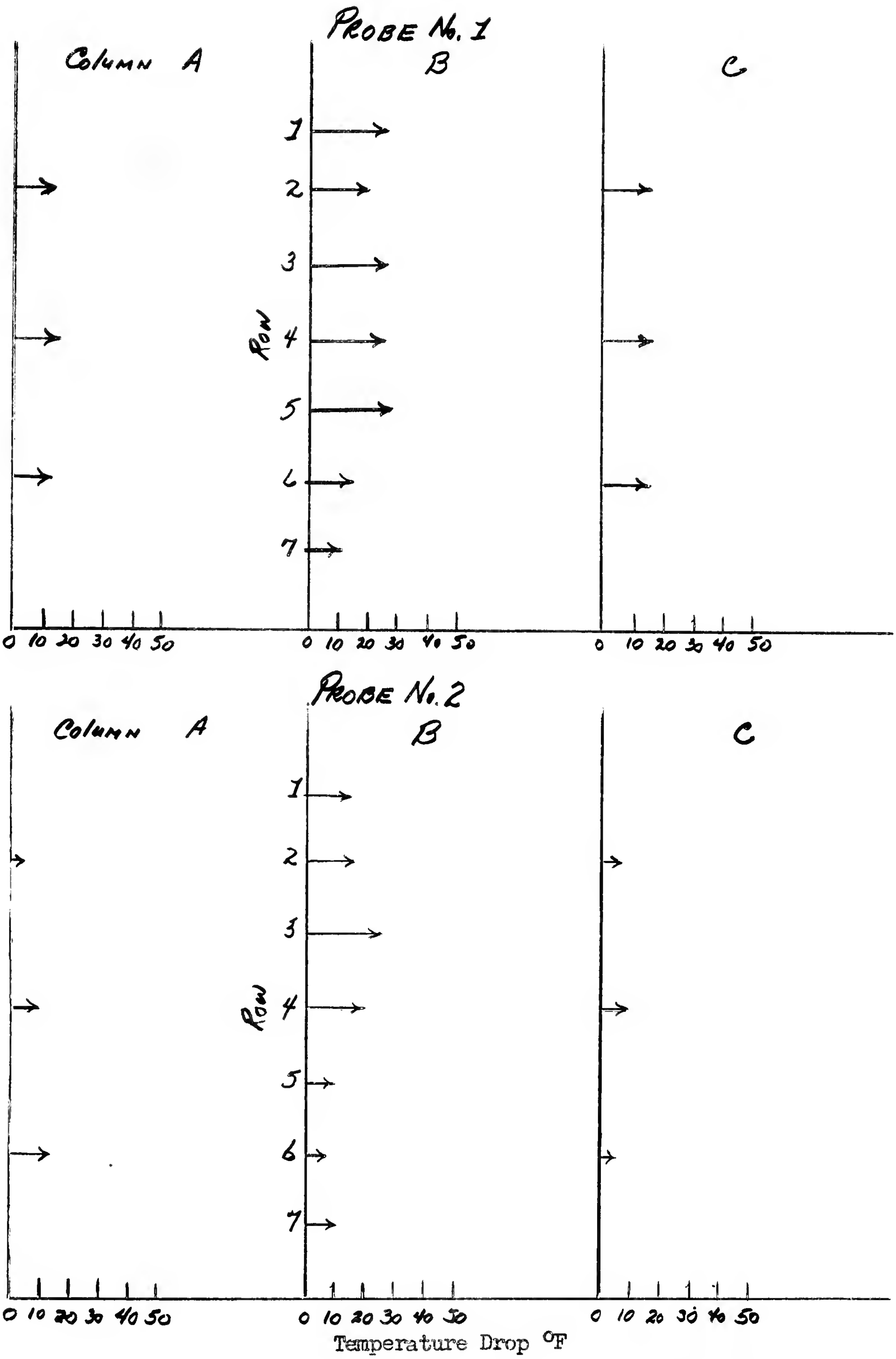


Figure 26. Temperature Drop Due to Fuel Vaporization
Station No. 2, Velocity 101 fps, F/A 0.01014

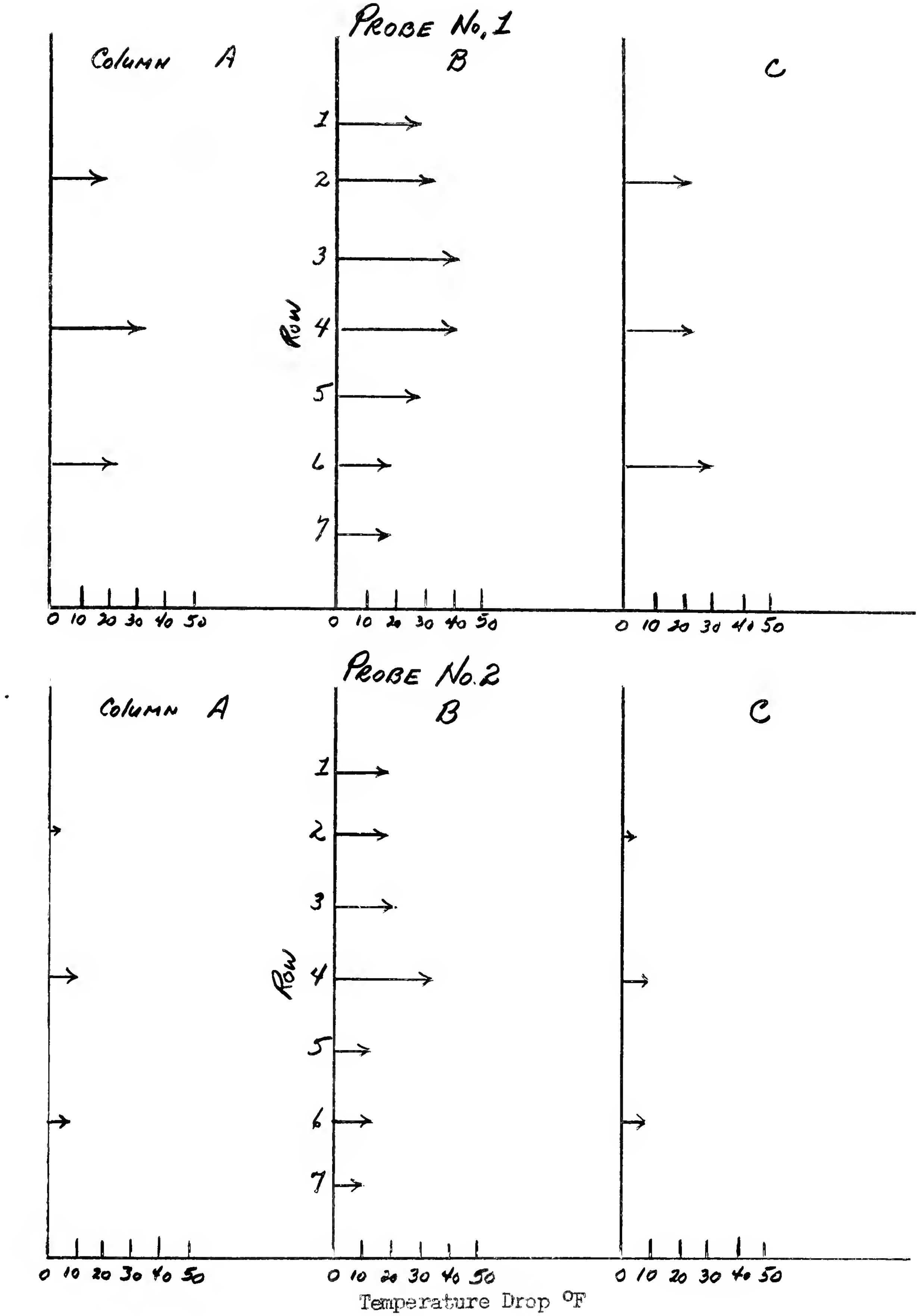


Figure 27. Temperature Drop Due to Fuel Vaporization
Station No. 1, Velocity 122 fps, F/A 0.00825

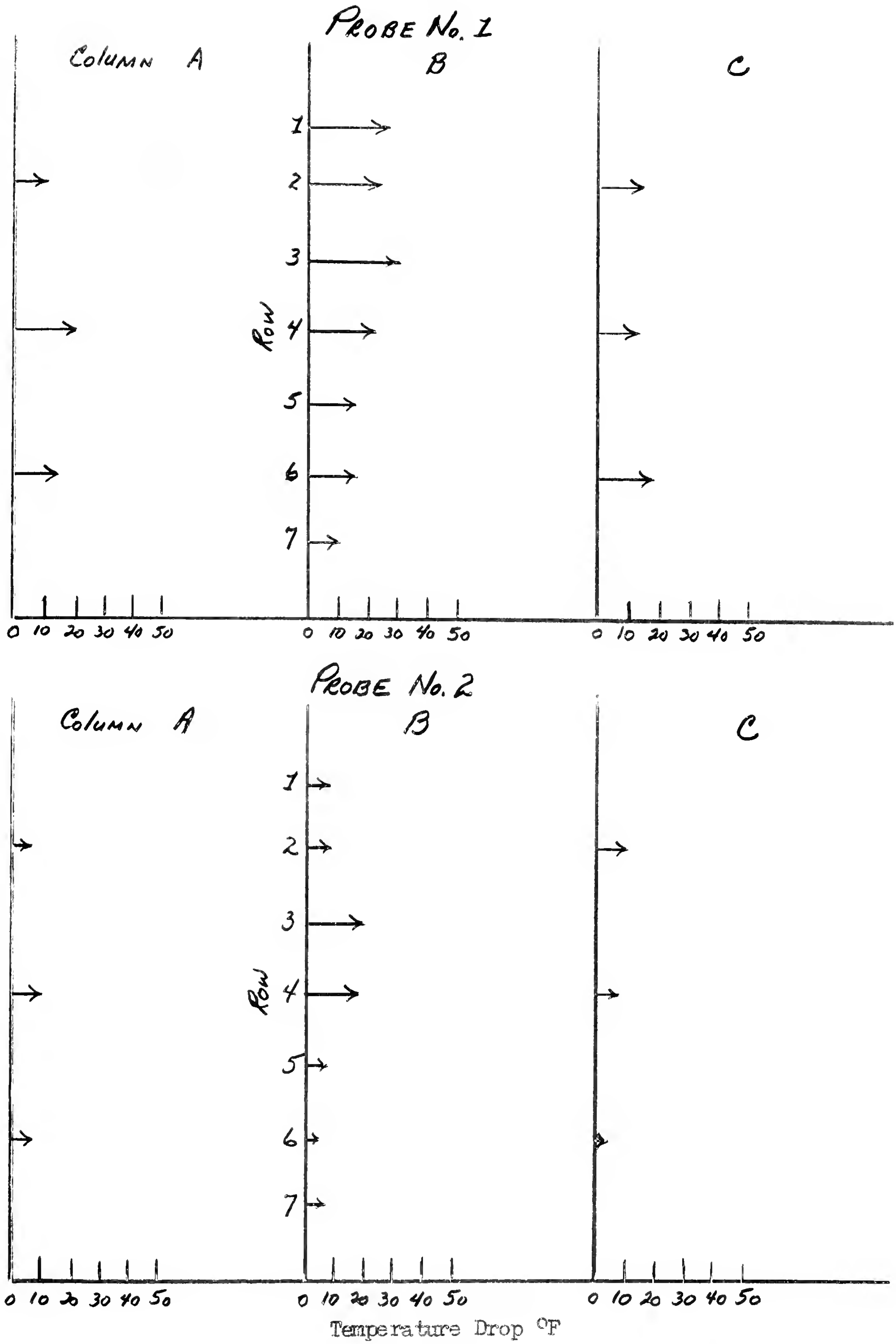


Figure 28. Temperature Drop Due to Fuel Vaporization
Station No. 2, Velocity 122 fps, F/A 0.00825

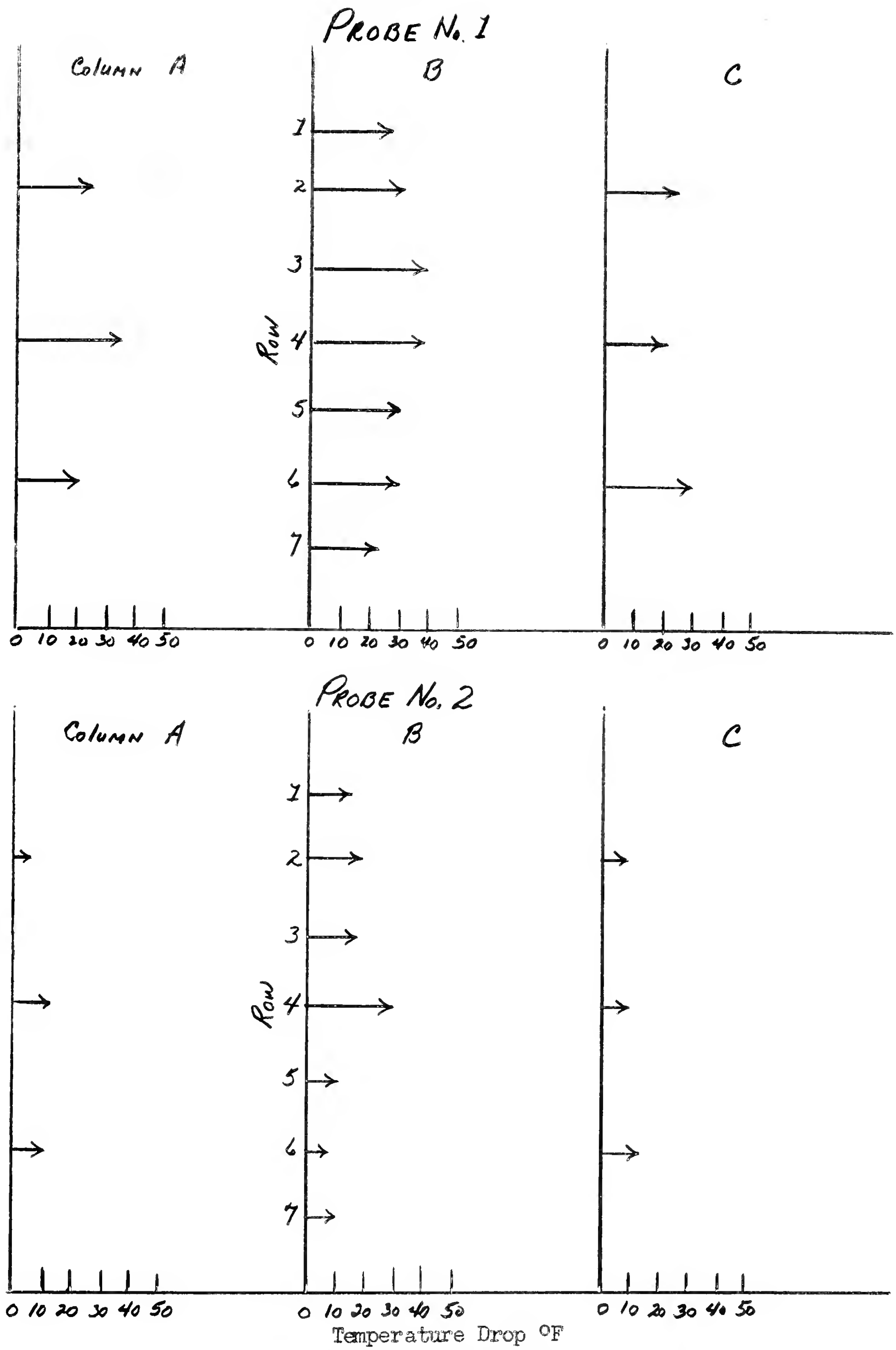


Figure 29. Temperature Drop Due to Fuel Vaporization
Station No. 1, Velocity 155 fps, F/A 0.00684

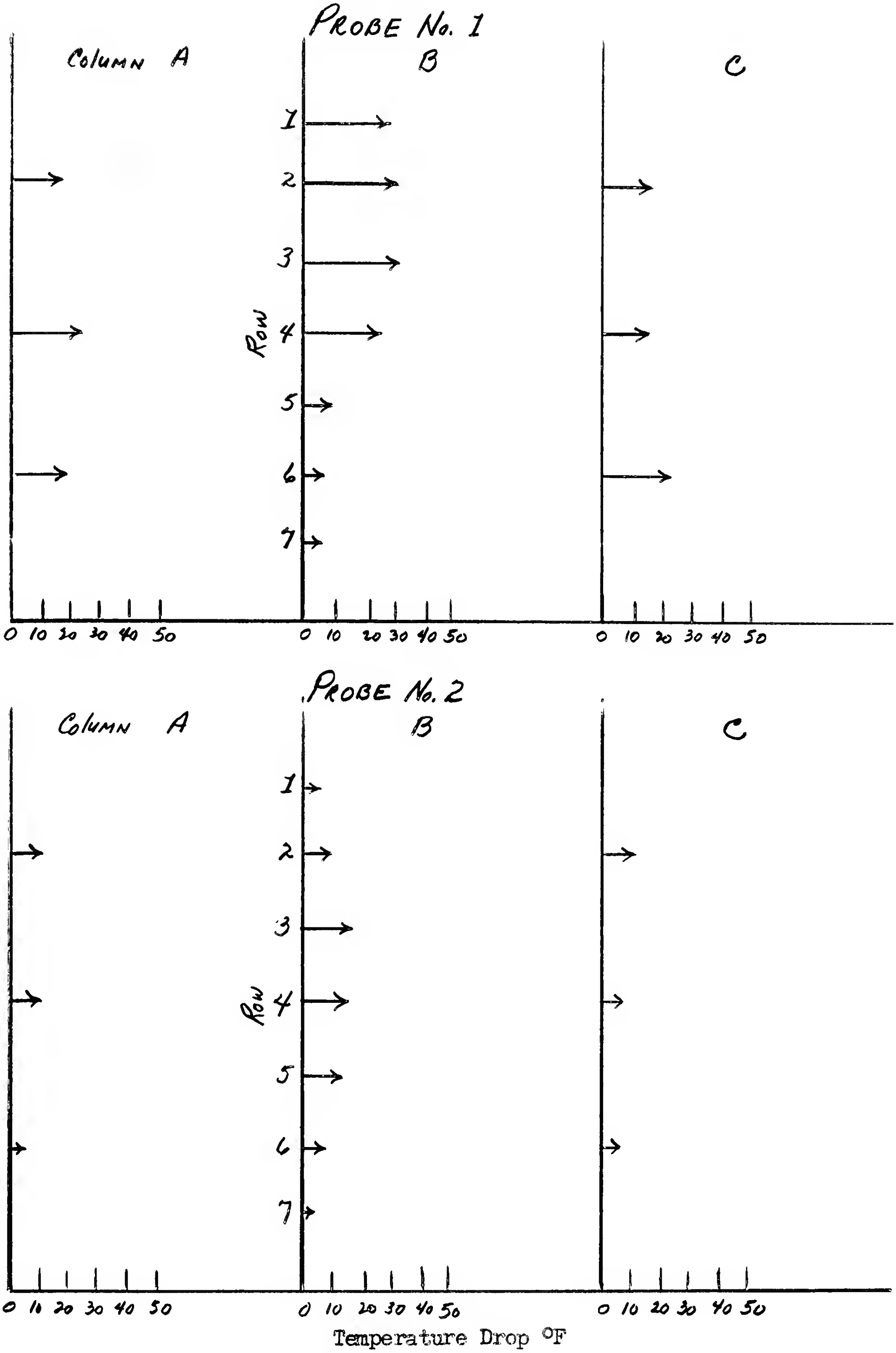


Figure 30. Temperature Drop Due to Fuel Vaporization
Station No. 2, Velocity 155 fps, F/A 0.00684

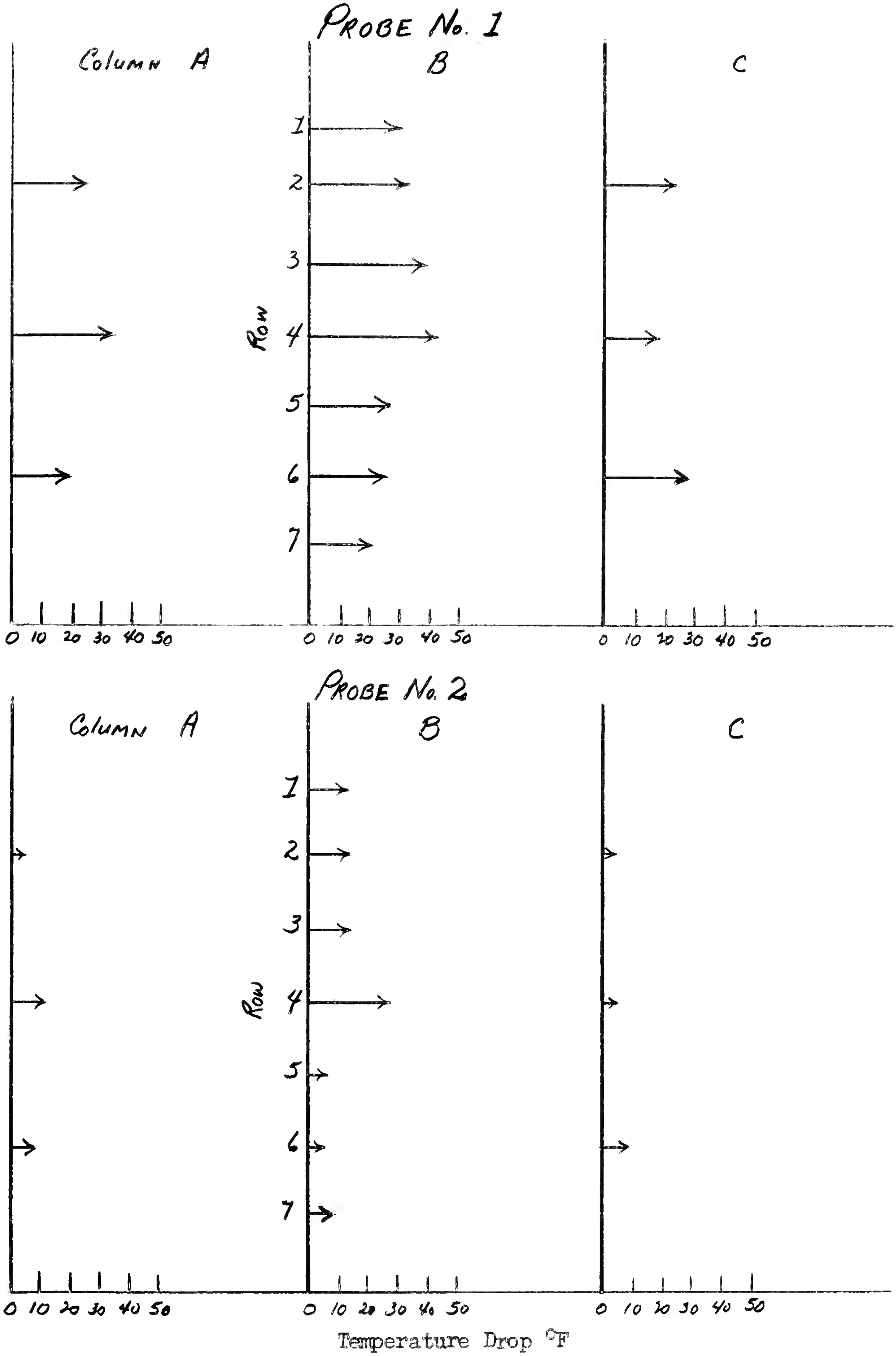


Figure 31. Temperature Drop Due to Fuel Vaporization
Station No. 1, Velocity 179 fps, F/A 0.00581

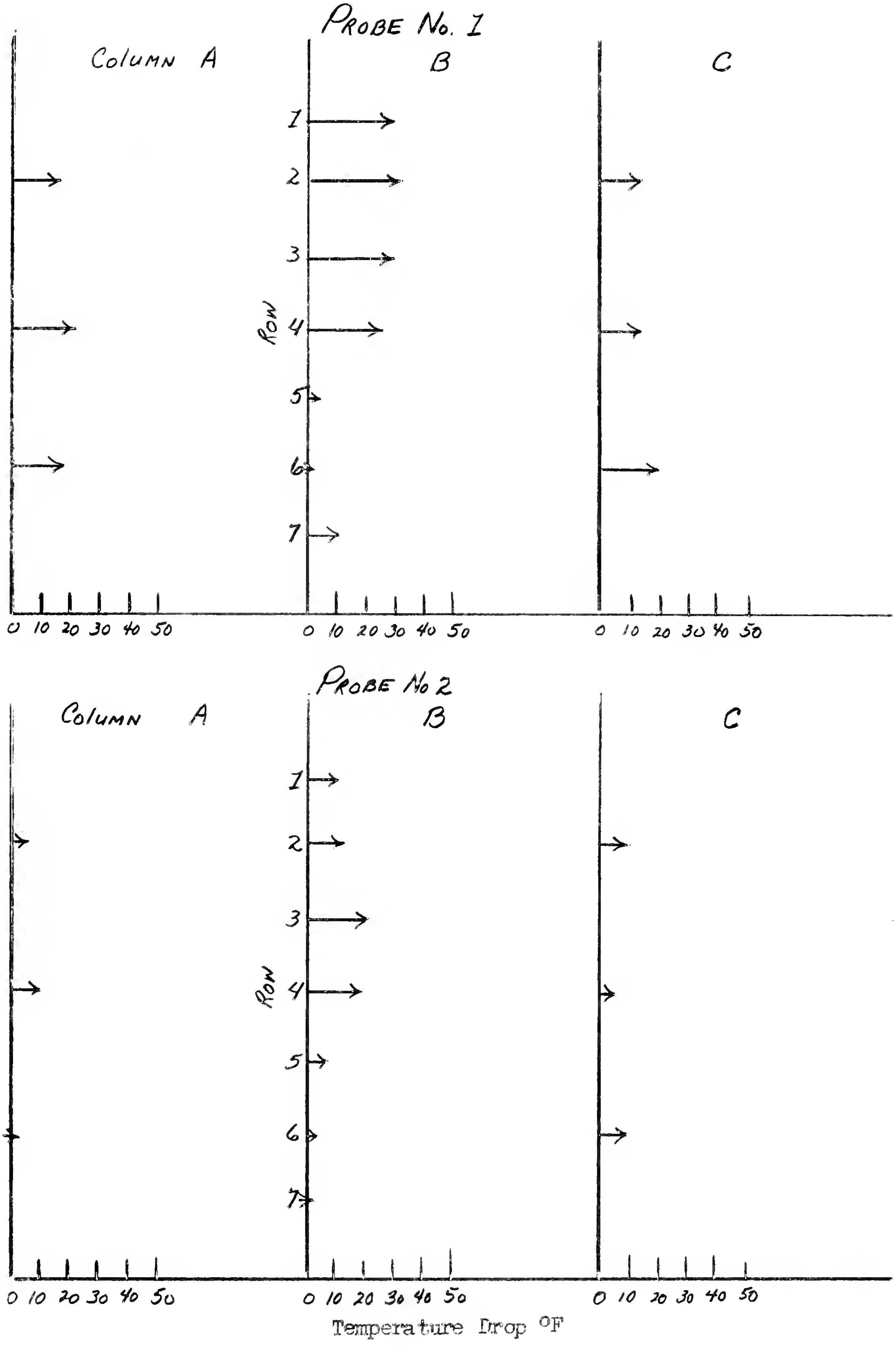


Figure 32. Temperature Drop Due to Fuel Vaporization
Station No. 2, Velocity 179 fps, F/A 0.00581

Table I. Temperature Drops Due to Fuel Vaporization

	Probe No. 1		Probe No. 2	
	Station No. 1	Station No. 2	Station No. 1	Station No. 2
Probe Position	Temp. Drop	Temp. Drop	Temp. Drop	Temp. Drop
		Velocity 101 fps		
A2	17	13	3	4
4	29	16	10	9
6	30	14	11	13
B1	33	26	18	15
2	36	20	15	16
3	44	26	18	25
4	45	26	30	20
5	30	28	22	9
6	27	15	16	7
7	27	12	10	10
C2	26	17	7	6
4	24	16	9	8
6	32	16	11	4
		Velocity 122 fps		
A2	20	12	4	6
4	33	21	10	10
6	23	15	8	7
B1	30	28	19	8
2	34	25	19	9
3	43	32	20	19
4	42	24	34	18
5	29	17	12	6
6	19	16	13	4
7	19	10	10	7
C2	23	16	4	10
4	24	14	9	8
6	30	19	8	3

Table II. Temperature Drops Due to Fuel Vaporization

Probe Position	Probe No. 1 Station No. 1 Temp. Drop	Probe No. 1 Station No. 2 Temp. Drop	Probe No. 2 Station No. 1 Temp. Drop	Probe No. 2 Station No. 2 Temp. Drop
		Velocity 155 fps		
A2	26	17	6	11
4	36	24	13	10
6	22	19	11	5
B1	28	30	15	6
2	32	32	19	10
3	40	32	17	17
4	39	27	30	16
5	31	10	11	14
6	31	7	8	8
7	24	7	10	4
C2	26	16	9	11
4	22	16	9	7
6	30	24	14	6
		Velocity 179 fps		
A2	26	16	4	5
4	34	22	11	10
6	20	17	8	1
B1	31	30	14	11
2	34	32	14	13
3	40	30	15	20
4	44	26	28	18
5	28	4	7	6
6	26	2	6	3
7	22	11	9	1
C2	25	14	5	9
4	19	14	5	5
6	29	20	9	9